LLNL Triennial Climate Scientific Focus Area Review

Improving Consistency between Cloud Parameterizations in CAM5

9/5/12

Peter Caldwell

Staff Scientist

Lawrence Livermore National Laboratory

PCMDI

Program for Climate Model Diagnosis and Intercomparison

CAPT

Cloud-Associated Parameterizations Testbed

ESGF

Earth System Grid Federation

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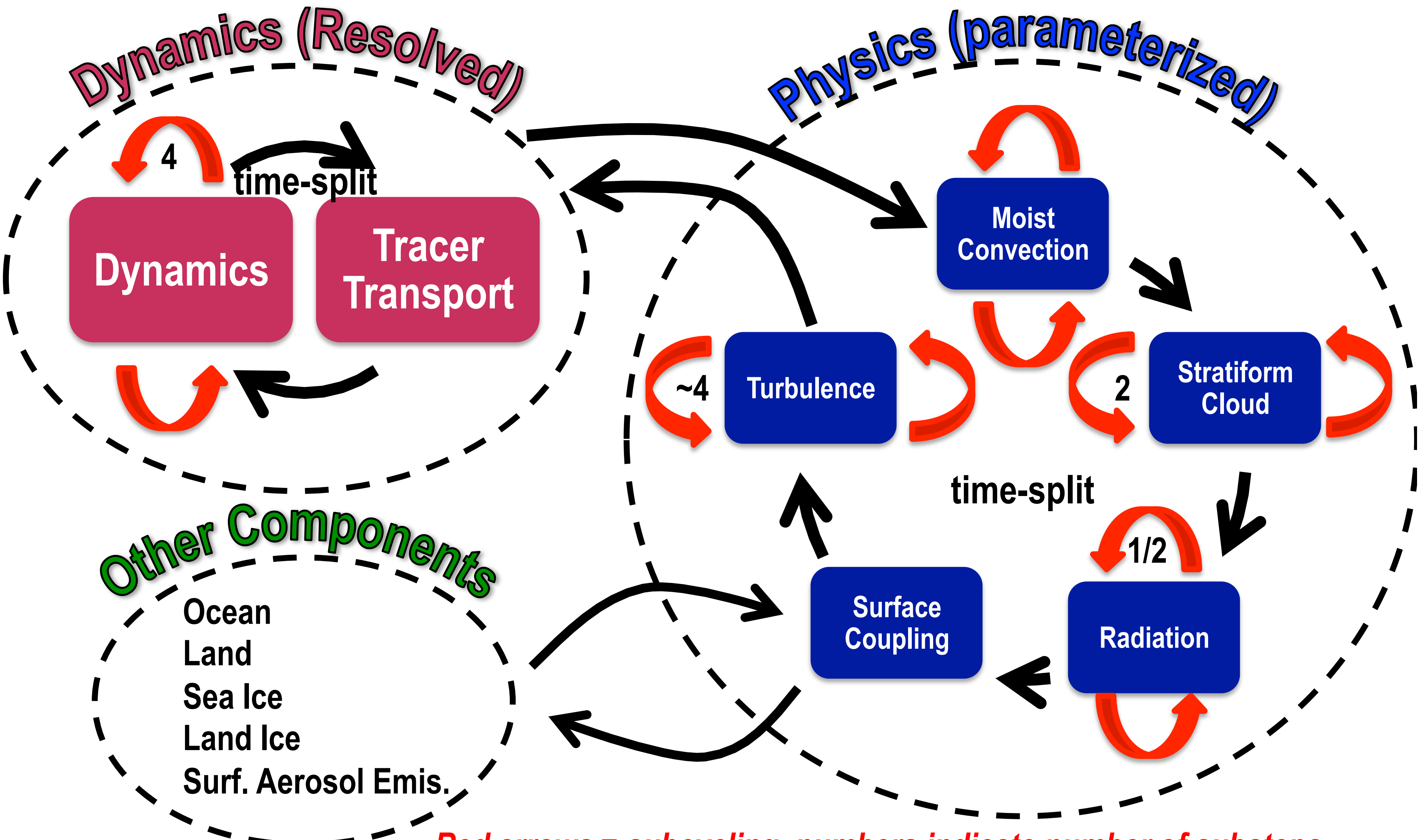
The Issue: Process Coupling



Red arrows = subcycling, numbers indicate number of substeps

Motivation:

- **GCMs are complex, so we tend to focus on individual processes**
  ⇒ Coupling between processes gets little attention

- **Over the last few years I have led an LLNL/NCAR/PNNL/JPL/UW effort to understand and improve coupling between stratiform cloud parameterizations**

- **I will show that this work has tremendous benefit. For example:**
  - **2 W m^{-2} (13%) improvement in shortwave cloud forcing RMS error**
  - **10 g m^{-2} (20%) increase (improvement) in global-average LWP**
  - **8% increase in model efficiency**

and there is much more to be done…

Outline

I. Four concerns (and suggested fixes)
   1. Cloud fraction/condensate (macrophysics) inconsistency
   2. Macro/microphysics subgrid-scale inconsistency
   3. Microphysics runs out of cloud water
      a. Time integration trouble
      b. Macro/microphysics decoupling
   4. Microphysics sees inconsistent cloud mass and droplet number

II. Impact of fixes on model climate

Issue #1: Cloud Fraction/Condensate (Macrophysics) Coupling

In CAM5:

1. Liq cloud fraction A_l from triangular PDF with width mimicking Rh_{crit} from CAM4
2. Liq condensate q_l is computed to satisfy:

given given given

$$RH_{in-cld} = 1 = f(q_t, q_l, q_i, T_c, A_l) \Rightarrow \frac{dq_{l,in-cld}}{dt} \approx \alpha \frac{dq_t}{dt} + \beta \frac{dq_l}{dt} + \chi \frac{dq_i}{dt} + \delta \frac{dT_c}{dt} + \varepsilon \frac{dA_l}{dt}$$

- *Condensational heating changes cloud fraction, handled via iteration.*
- *Consistency between A_l and q_l ensured via "if" statements*

constraint:

$$\boxed{\frac{dq_l}{dt} = A_l \frac{dq_{l,in-cld}}{dt} + q_{l,new} \frac{dA_l}{dt}}$$

$$\boxed{\frac{dA_l}{dt} \approx \frac{A_{l,new} - A_{l,old}}{\Delta t}}$$

In New Scheme:

- Cloud fraction and condensate *both* computed assuming a truncated Gaussian PDF
- PDF width and ice are treated ~ as in default model

$$\boxed{\text{Cloud Fraction} = \int_0^\infty PDF(s)\,ds} \quad \boxed{\text{Cloud Mass} = \int_0^\infty s \cdot PDF(s)\,ds}$$

saturation excess $s = q_t - q_i - q_s(T,p)$

Benefit:

- Single parameterization for q_l & A_l improves consistency, simplicity, and efficiency

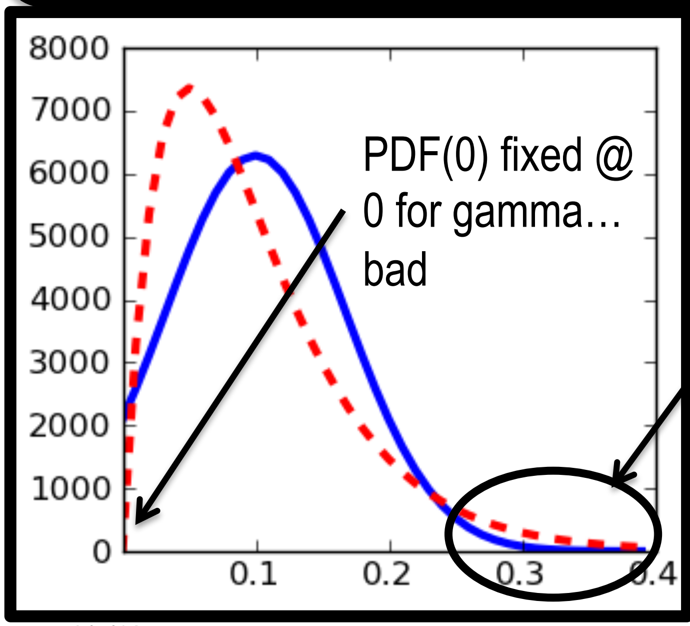
Issue #2: Inconsistent SGS Assumptions between Macro/Microphysics

In CAM5:

- Subgrid-scale (SGS) variability in q_l is assumed to follow a **gamma** distribution for **autoconversion**, **accretion**, and **droplet freezing** calculations which is inconsistent with the Gaussian or triangular PDF assumed in macrophysics

In New Scheme:

- The Gaussian PDF used for macrophysics is truncated at s=0 and used for these processes. Implemented as table-lookup⇒efficient



Impact:

- +skewness & PDF(0)=0 make Gamma tails larger ⇒ new scheme should have generally weaker process rates

Fig: Gaussian (blue) vs Gamma (red) PDF for same atmospheric state.

Issue #3: Total Microphysical Liquid Depletion

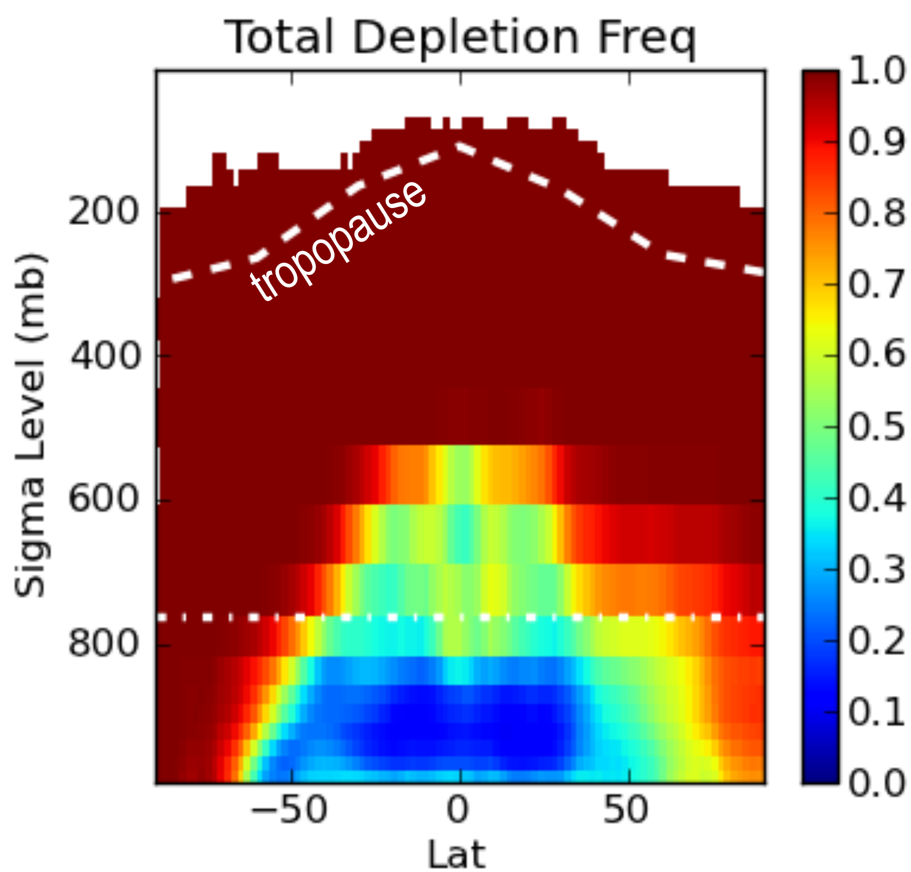
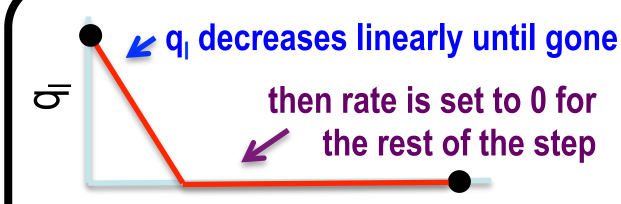


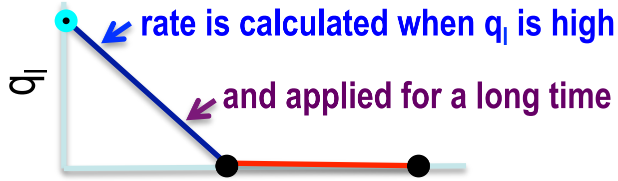
Fig: Zonal-ave frequency of microphysics starting with >1e-3 g/kg of liquid and depleting it in a single step (from last 9 yrs of a 10 yr current-climate AGCM run)

- Clouds are always flickering on and off in CAM5 microphys
  - Bad because cloud dissipation is crude:



Issue #3 (cont'd): Why the flickering? How to fix?

@ 2 micro substeps (default):



With more substeps:

Fig: Time integration scheme in CAM5 microphysics

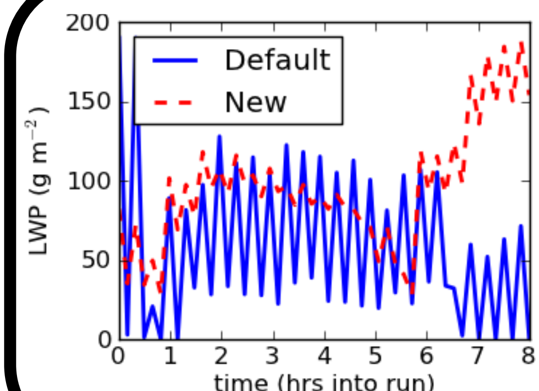


Fig: LWP after macro & after micro from SCM MPACE-B run

Numerical Concerns:

1. **Microphysics uses forward Euler timestepping with 2 substeps**
   - **Overpredicts since dq_l/dt decreases as q_l gets smaller**
2. **Macrophysics (condensation +cldfrac) typically creates q_l, while microphys depletes q_l**
   - **Sequential splitting of macro+micro makes total depletion more likely, increases system stiffness**
     - **# micro substeps originally tested with macro+micro coupled!**

Issue #3 (cont'd): Impact of Increasing Substeps

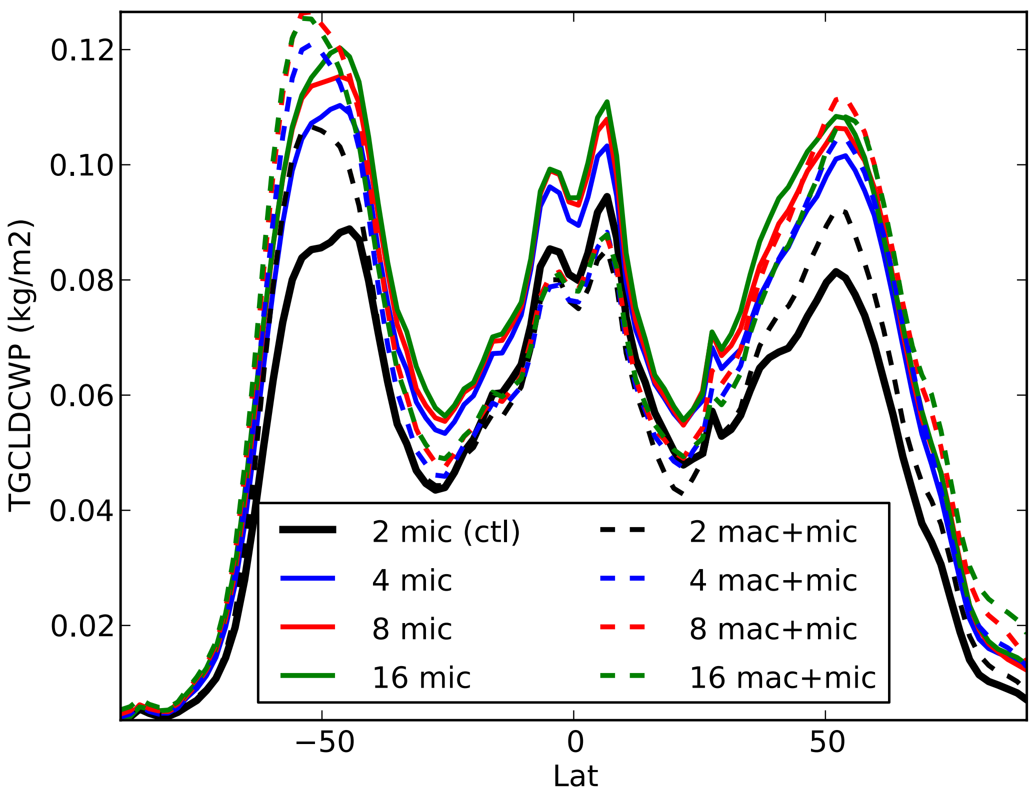


Fig: Effect of increasing the number of macro (mac) and/or microphysical (mic) substeps. Values are zonal and time-averages from the last 4 yrs of 5 yr current-climate AGCM runs.

- Substepping micro =test of error from forward-Euler
  - Midlat LWP depressed 25% by time truncation error!
- Substepping mac +mic together=test of decoupling error
  - mac+mic coupling has a big impact in the tropics

Issue #3 (cont'd): Is depletion caused by time truncation issues?

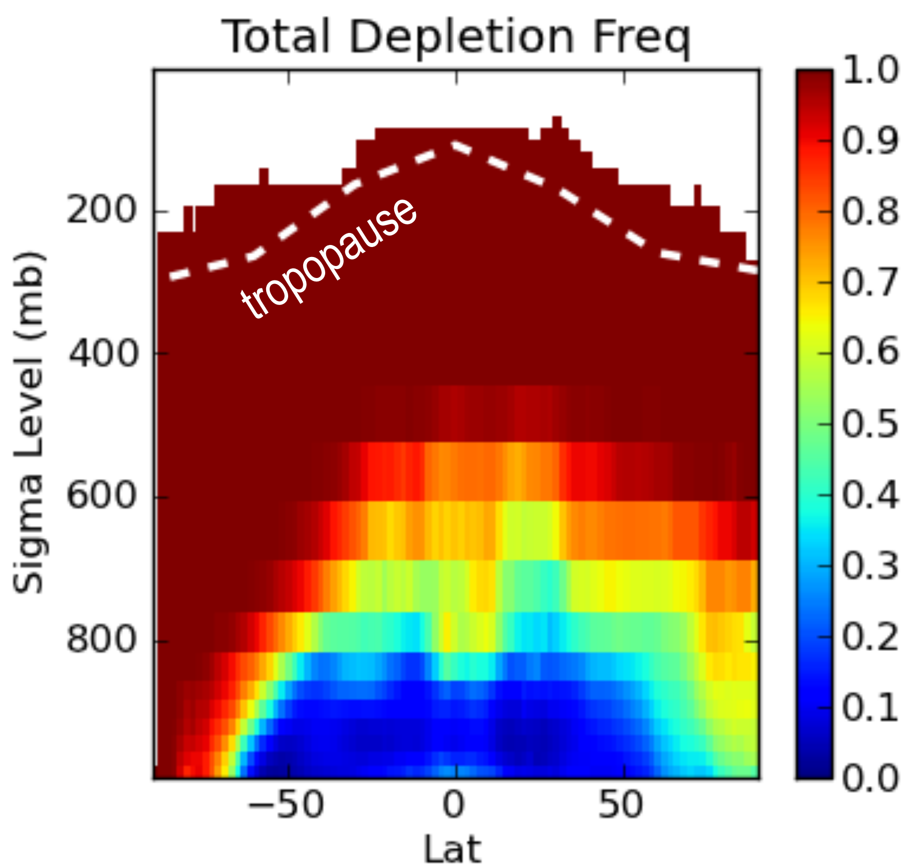


Fig:Total depletion frequency (as in previous slide), but based on a simulation using 4 mac+mic substeps.

- **No… So what else is happening?**

Issue #3 (cont'd): Another Perspective on Microphysical Depletion

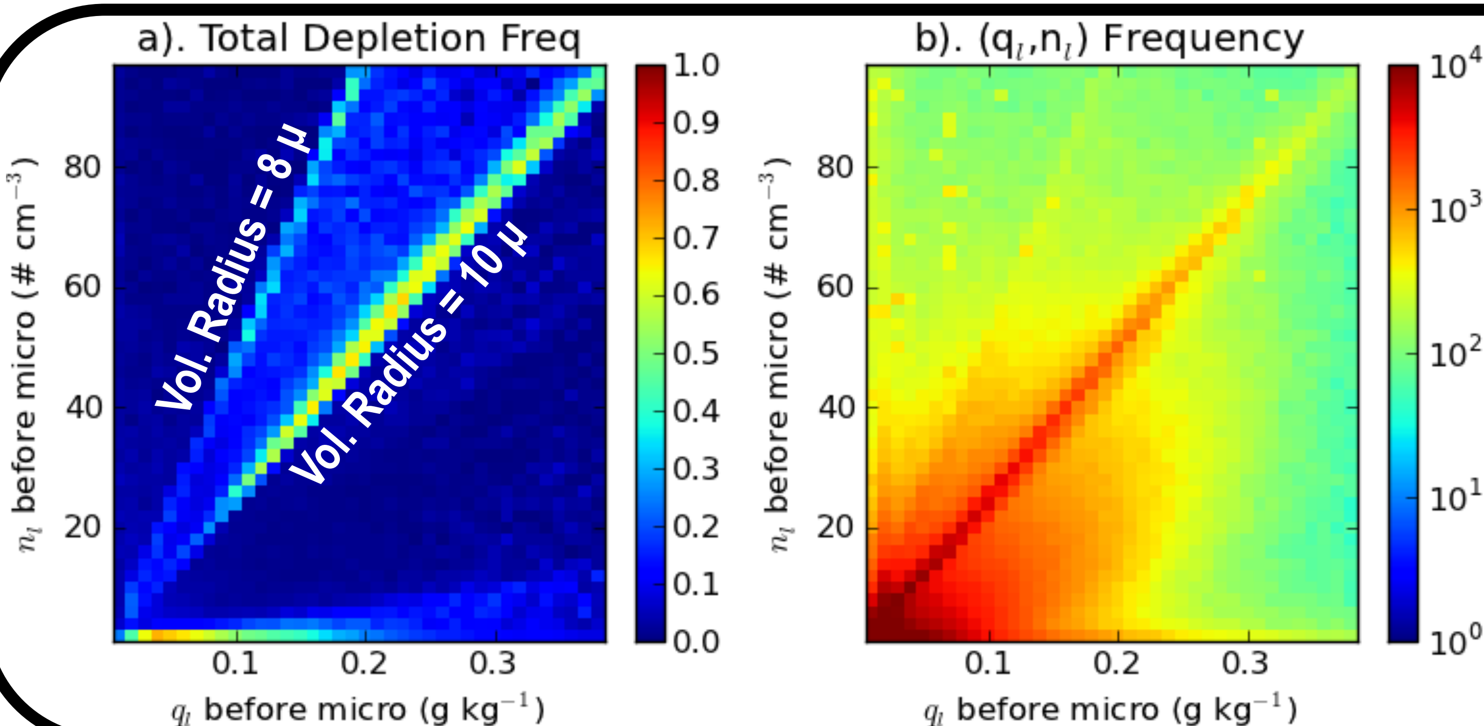


Fig: a). Freq of total micro depletion as a function of (q_l,n_l). b). Freq of sampling the various (q_l,n_l) states. Data from ~750 mb level of 1 month-long current-climate AGCM run

- **Depletion is only frequent at very low n_l and on 2 bands… which are the most frequent states.**
  - **these bands result from detrainment occurring at 10μ and 8μ mean volume radii for shallow and deep convection (respectively)**
- **Perhaps depletion *should* occur under these conditions? The mystery continues…**

Issue #4: LWC/Droplet # Inconsistency

In CAM5:

Macro creates q_l, Activ creates n_l → **Micro procs** → **½ of new n_l added** → **sed, rad, etc**

2 substeps

New q_l applied ***but not n_l***

In New Scheme:

q_l AND n_l are updated before microphysics

Impact:

ARSCL Obs Cloud Frac | **CAM5 Cloud Frac** | **Cloud Frac w/ this Fix**

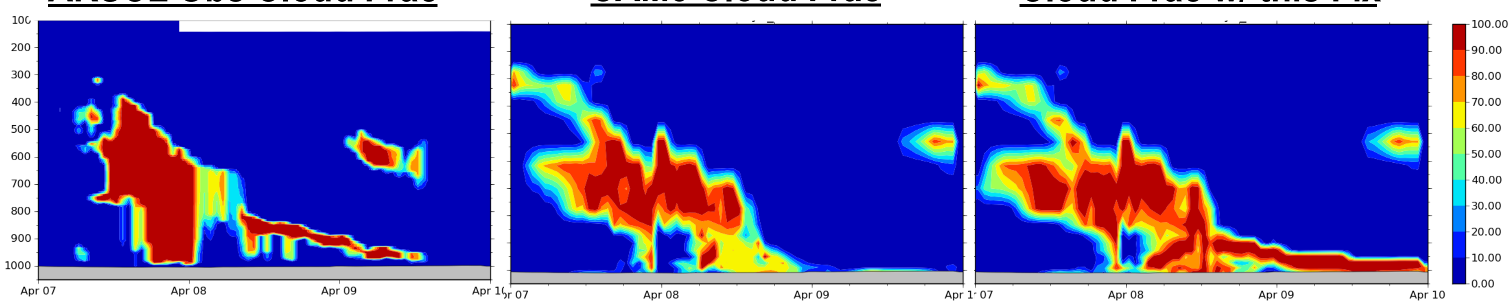
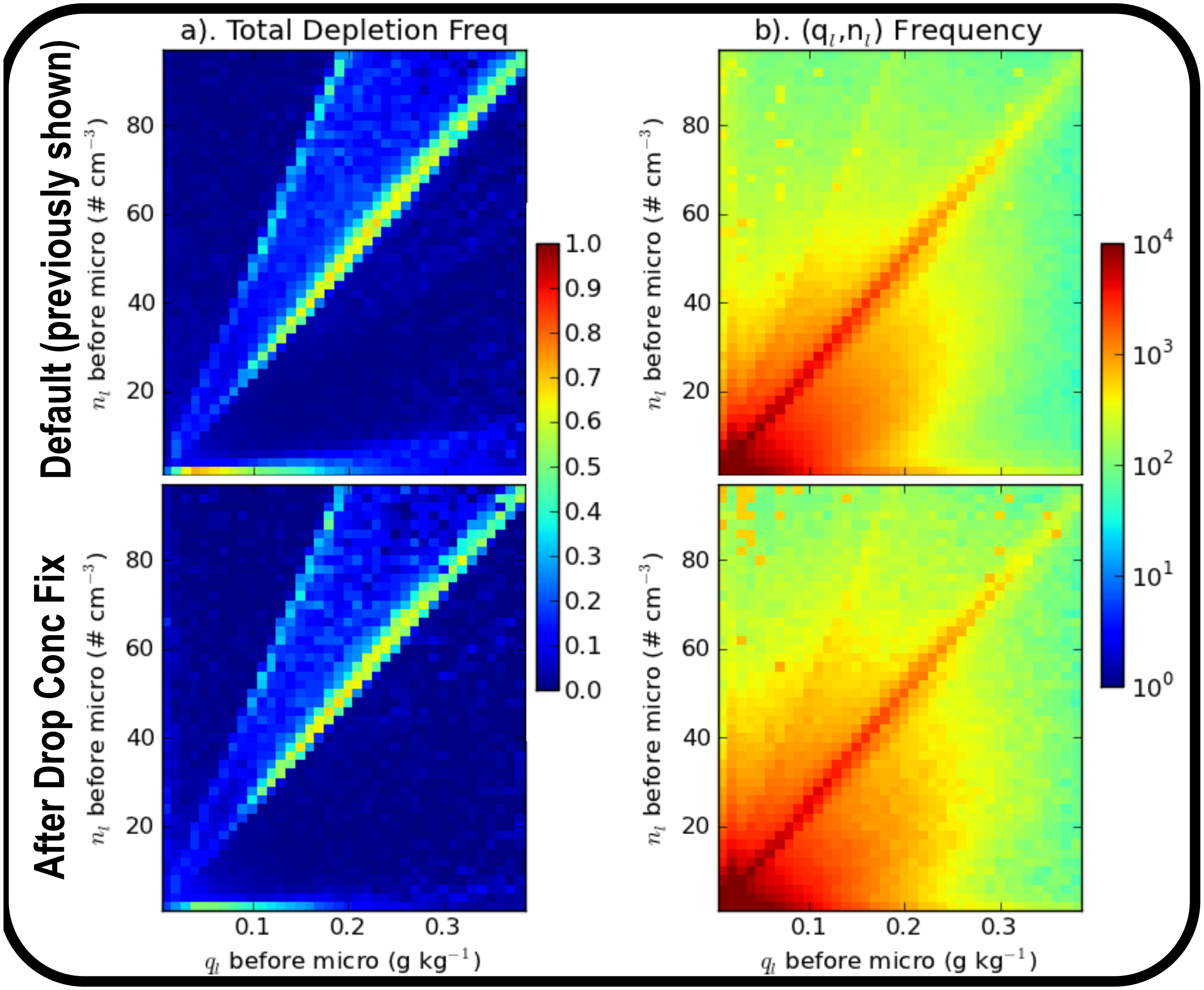


Fig: MERRA-driven 24-48 hr CAPT forecasts for ISDAC "Golden Day" (Courtesy J. Boyle)

Issue #4 (cont'd): Effect of Droplet Concentration Fix



- **fixing n_l inconsistency doesn't help**

Fig: As in prev. slide, but bottom panels show result once n_l inconsistency is fixed.

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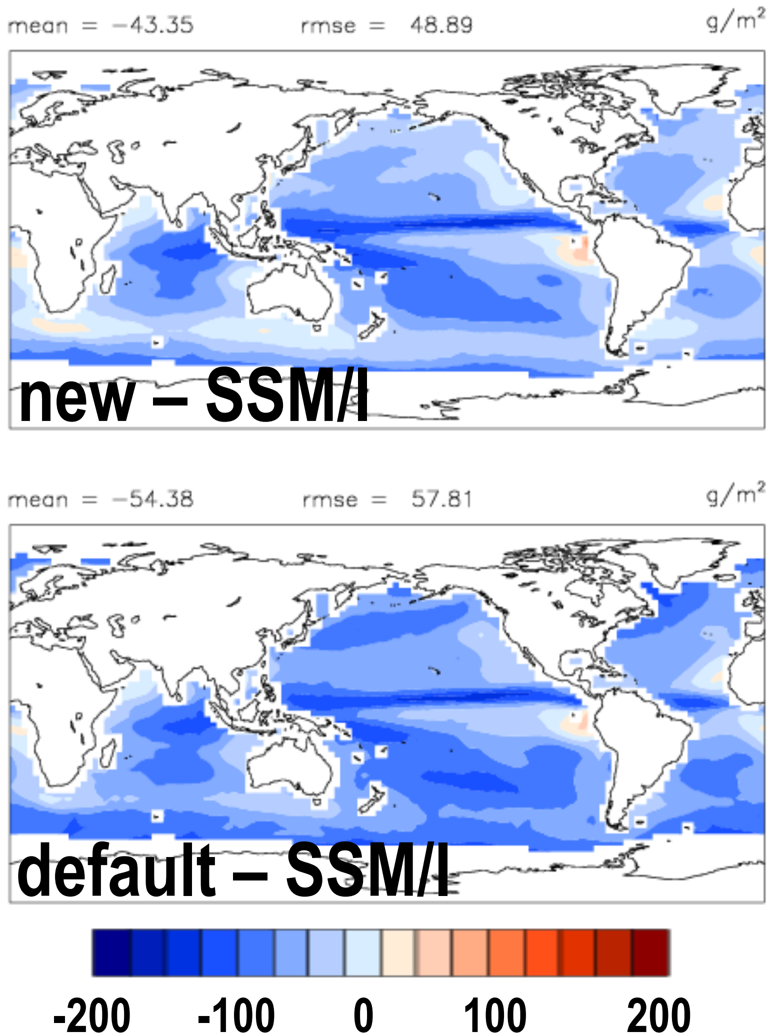
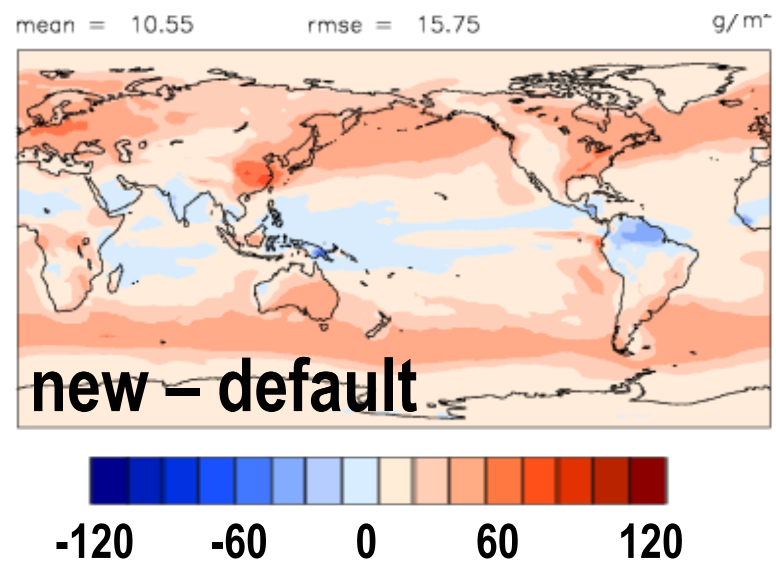
II. **Impact of fixes on model climate**

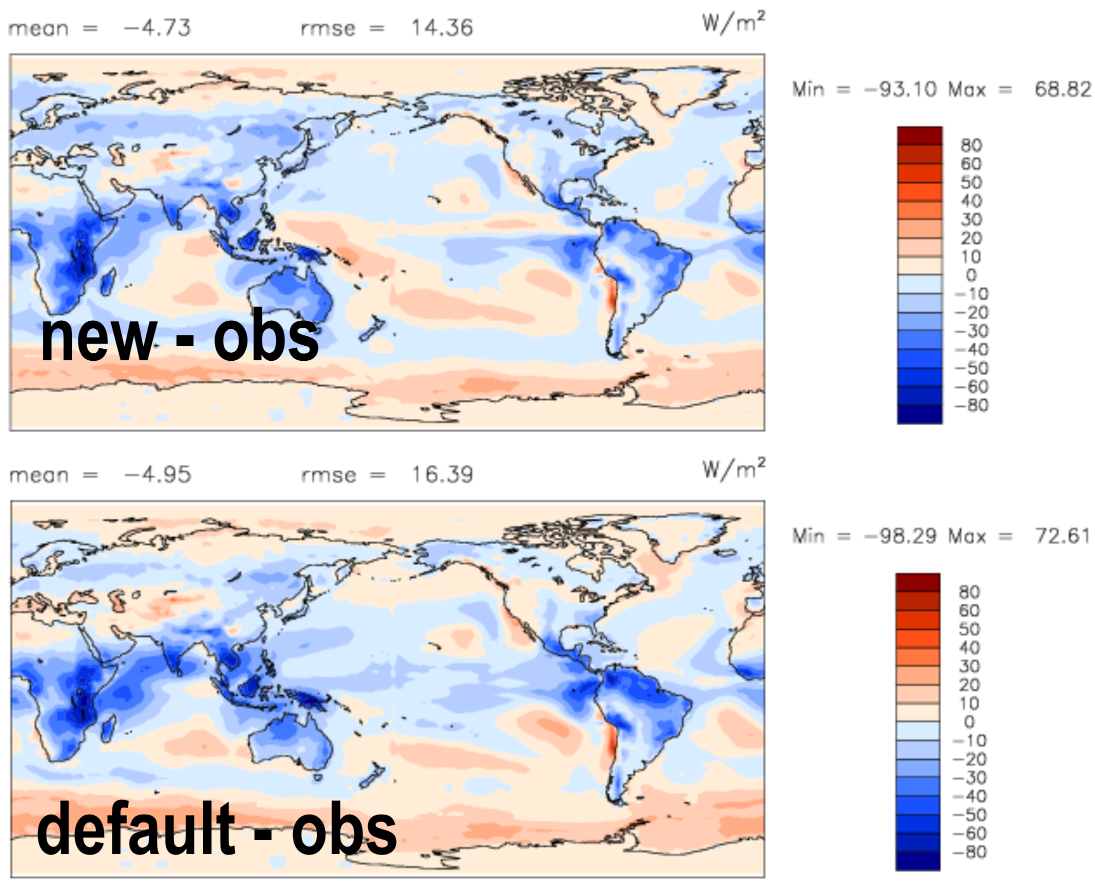
Liquid Water Path (LWP)





- **Increases in storm tracks, decreases in tropics**
- **LWP bias and RMSE are greatly improved**
- **Change due to n_l, q_l consistency fix, Gaussian microphysics, & micro substepping**

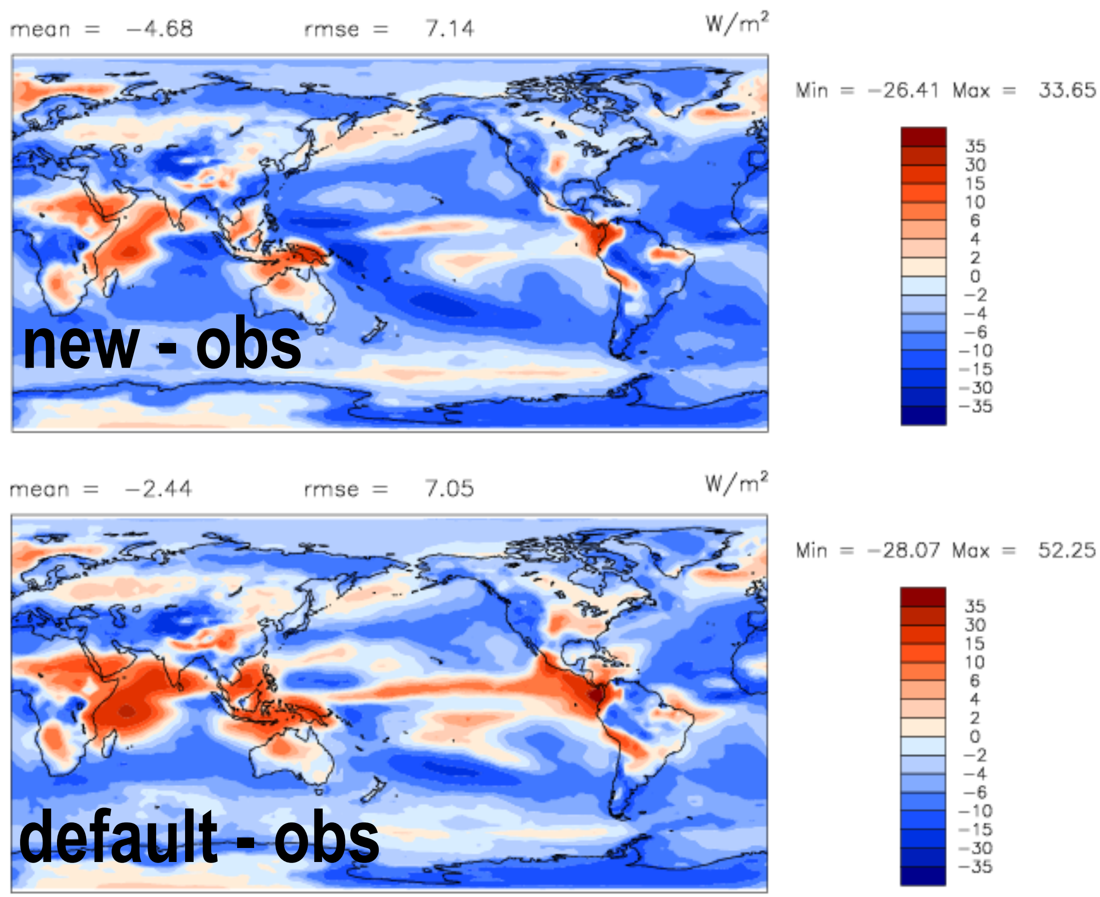
Shortwave Cloud Forcing (SWCF)



- **SWCF improves**
- **TOA net rad = 2.1 W m^{-2} versus -1 W m^{-2} for new**

Fig: Shortwave Cloud Forcing (SWCF) bias from default and new runs. Obs = CERES-EBAF

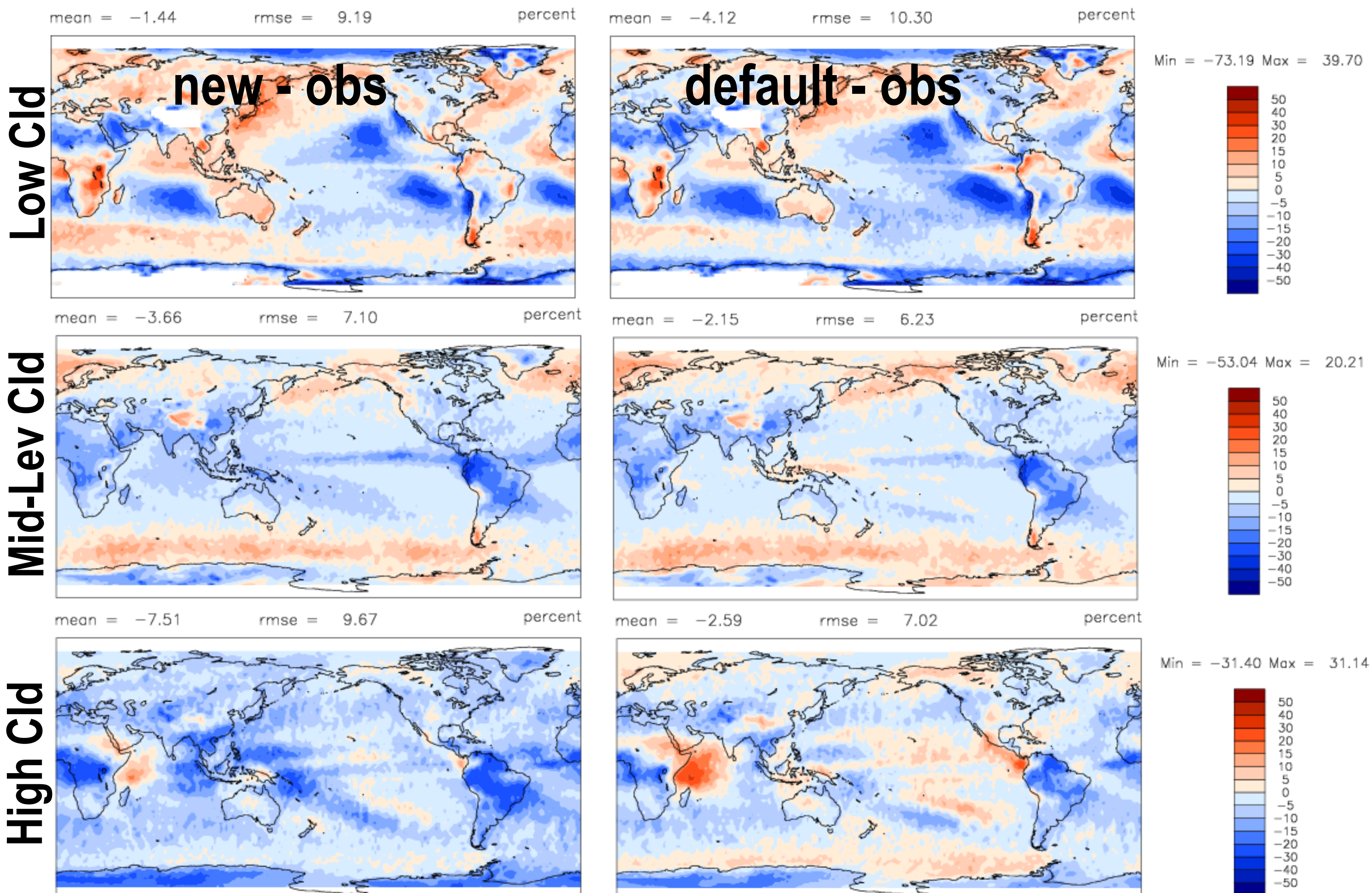
Longwave Cloud Forcing



- **LWCF skill ~unchanged**
- **OLR improves by 1.8 W/m² (not shown)**
- **Less high clds ⇒ less +bias in convective regions, more - bias elsewhere.**

Fig: Longwave Cloud Forcing (LWCF) bias from default and new runs. Obs = CERES-EBAF

Cloud Bias: CALIPSO (COSP)



Cloud changes are predominantly due to new macrophysics

Other Results:

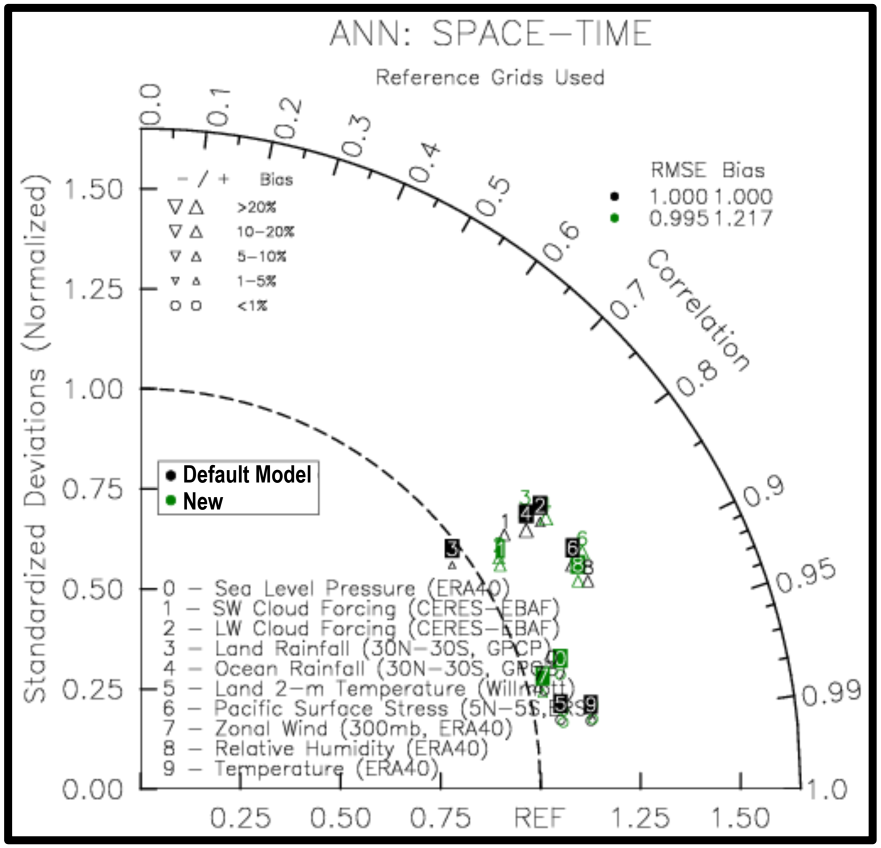


Fig: Taylor plot from untuned 10 yr Y2K climo-SST runs

- New version has overall Taylor skill scores similar to default configuration
  - skill ~unchanged for surface pressure & temperature, winds, and precipitation
- New macrophysics code is 4x faster
  - Version with substepped macro +micro is *not* faster due mainly to extra aerosol, cloud sedimentation, and vapor deposition calls

- Climate sensitivity ~unchanged (3.9 K vs 4.1 K for default, computed following Gettelman et al, JClim 2012)
- Aerosol sensitivity increases slightly (ΔSW_{net} = -0.02 W m^{-2}, ΔLW_{net} = -0.1 W m^{-2})

Conclusions:

We have identified and fixed 4 issues related to coupling between non-convective cloud processes

a. **LWP and SWCF are greatly improved, other variables ~unchanged**
b. **Our truncated Gaussian macrophysics is much more efficient**

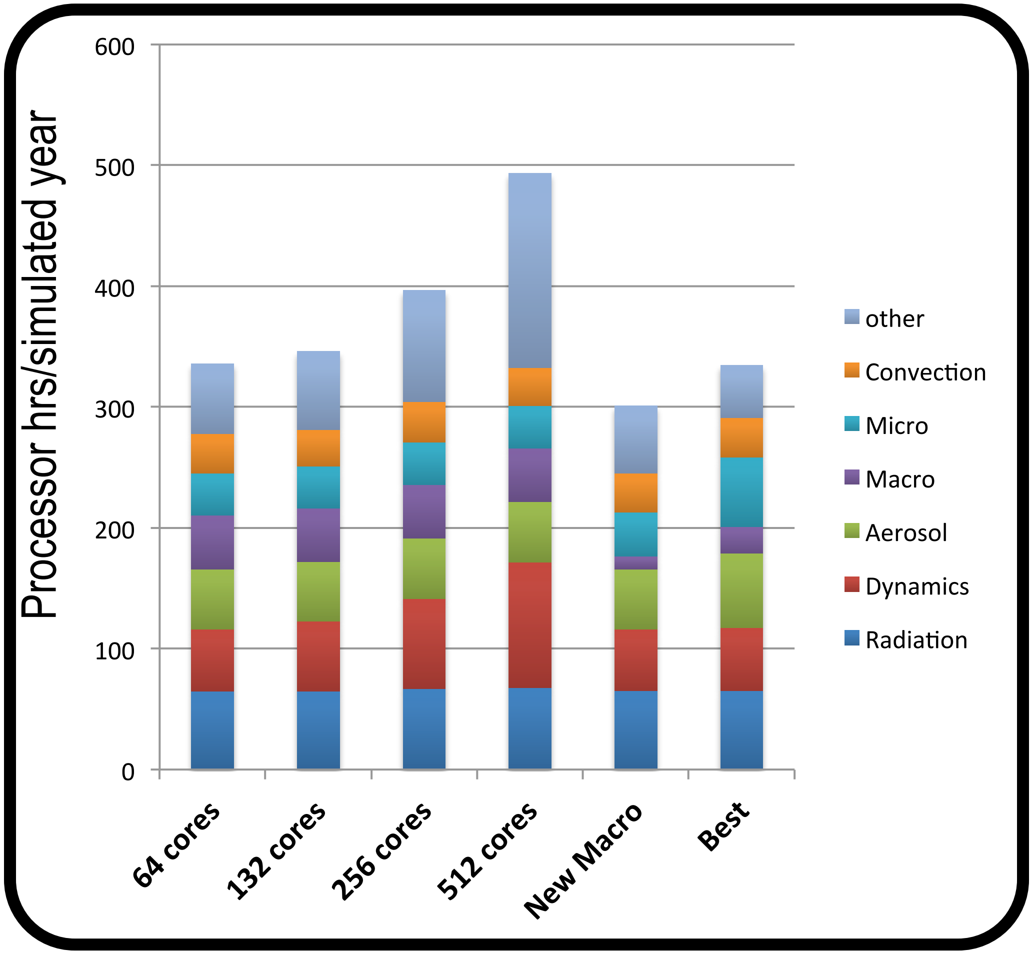
Our changes are now being added to the developers' trunk. We are confident that at least some of them will become the default for future releases.

Future Work:

1. **Work with Morrison+Gettelman to improve treatment of total liquid depletion in microphysics**
2. **Identify source of depletion bands and fix if appropriate**
3. **Improve treatment of PDF variance**
4. **Add ice-phase to PDF**
5. **Extend sub-column generator to include q_l variability**
6. **Extend analysis beyond stratiform cloud components**

Extra Slides

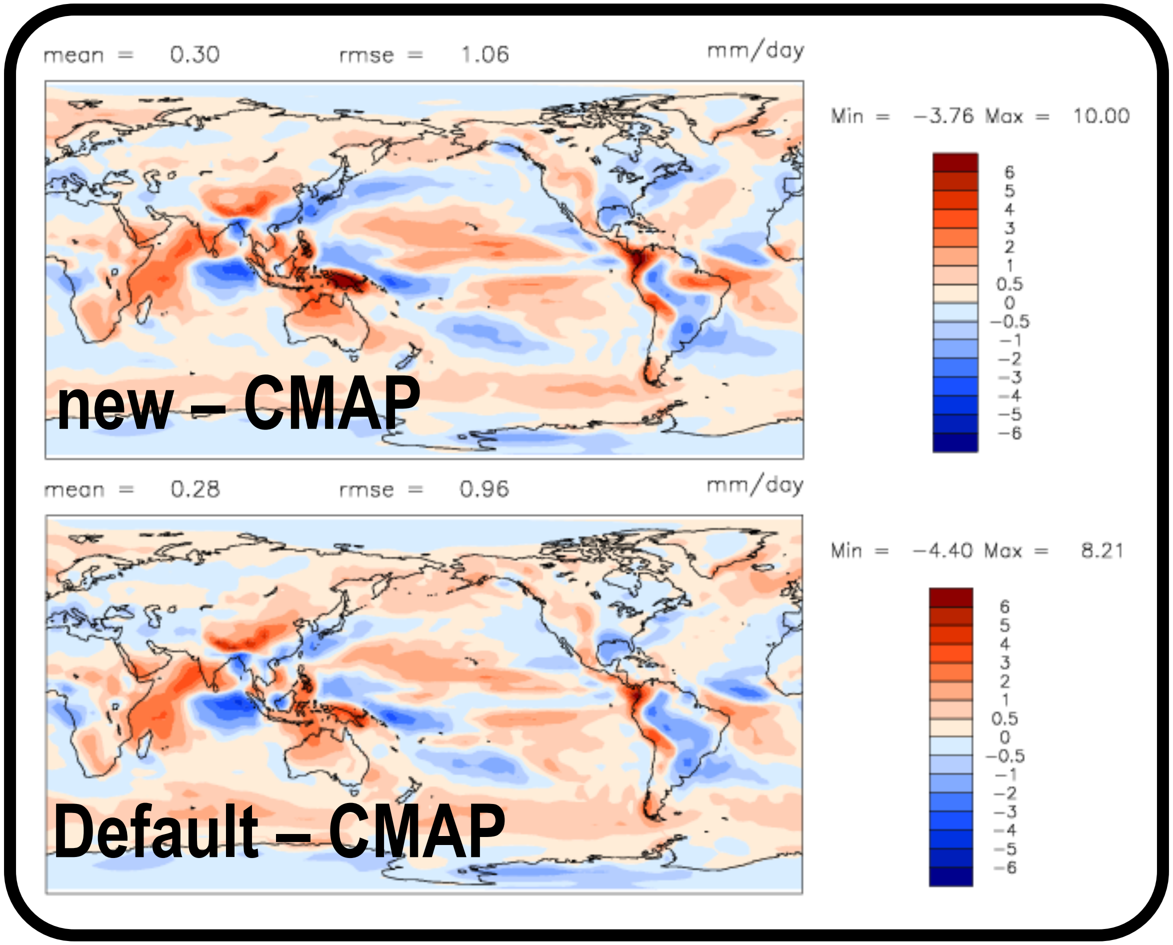
Timings:



- **Physics scales perfectly, dynamics + other (e.g. coupling) doesn't**
- **PDF macro *much* faster**
- **Substepping macro+micro removes this advantage (due to increased nucleation + micro)**

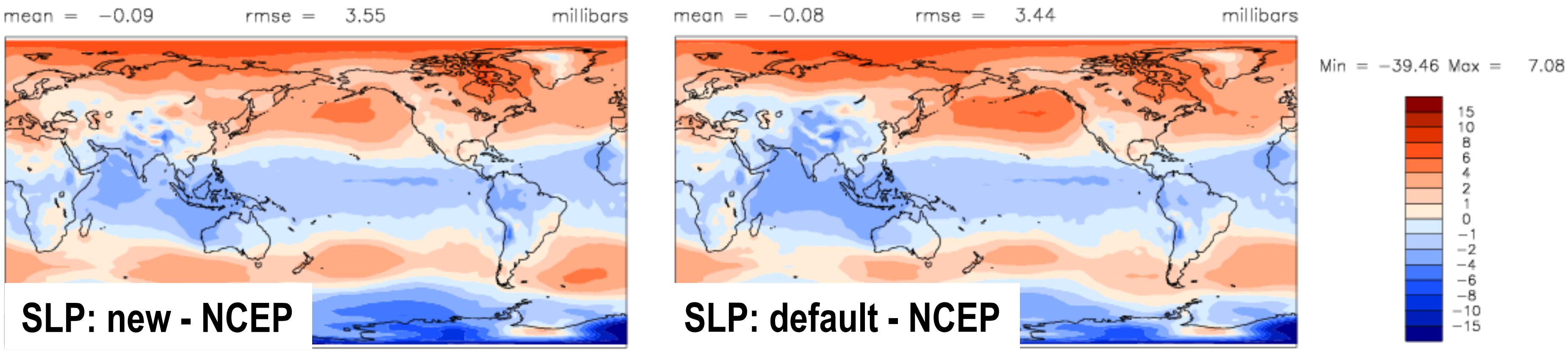
Fig: Time (summed over cores) spent in each of the physics procs for a 1 year fixed-SST run for various model configurations (from Dan Bergmann).

Precipitation



- **Precip slightly worse in new ver**
  - **+bias amplifies over tropical land, otherwise precip decreases**
- **Main source of precip differences is macro +micro substepping (not shown)**

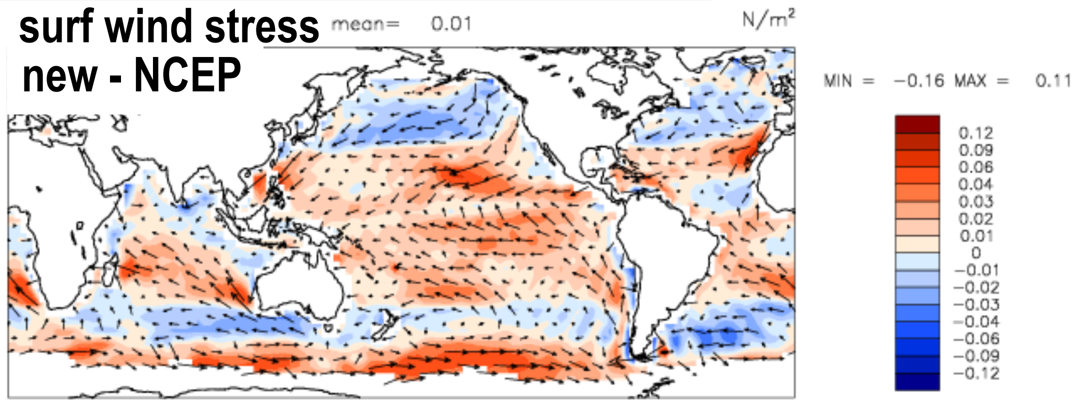
Dynamics



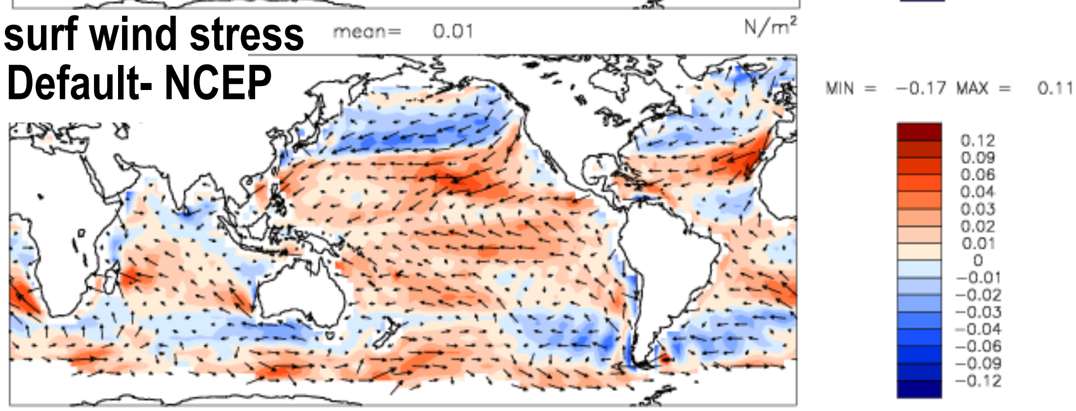
SLP: new - NCEP

SLP: default - NCEP

surf wind stress
new - NCEP



surf wind stress
Default- NCEP



- **SLP bias ~unchanged**
  - **Aleutian low better**
- **Surface stress also ~unchanged**

Aerosol Sensitivity

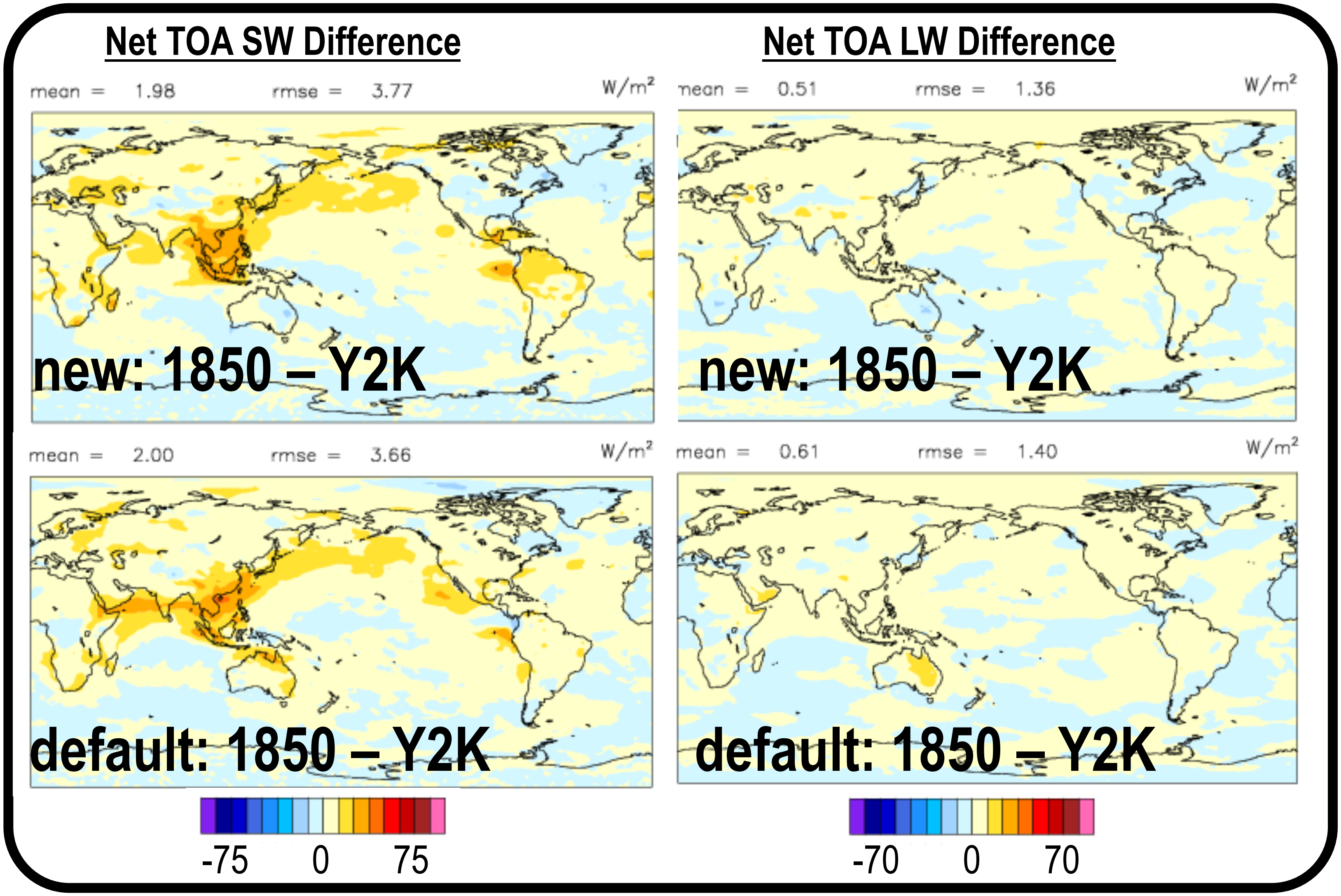


Fig:Effect of pre-industrial vs Y2K aerosol emissions on new and default CAM5.1 simulations. Based on 10 yr runs all using Y2K SST. Gaussian is NOT truncated for these runs.

Climate Sensitivity:

$\delta E = F - \Delta R$. Define $\lambda = \Delta R / \Delta T_s$.

Top-of-atmosphere energy imbalance

Radiative forcing from 2xCO2 (3.7 W/m2)

Radiative response to restore balance

Feedback parameter

Global-Ave Surf Temp

Then climate sensitivity (ΔT_s from 2xCO2)=

$$\gamma = -F/\lambda$$

$$= \Delta T_s / (\delta E/F + 1)$$

- **Can be used to get γ from AGCM run with 2xCO2 + patterned SST rise (Gettelman et al, 2012; JClim)**
- **Default CAM5 γ ≈ 4.1 K, our "best" case has γ = 3.9 K**